

PROJECT UM-HAUL: A SELF-UNLOADING REUSABLE LUNAR LANDER

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INTRODUCTION

The establishment of a lunar base is technologically and financially challenging. Given the necessary resources and political support, it can be done. In addition to the geopolitical obstacles, however, there are logistical problems involved in establishing such bases that can only be overcome with the acquisition of a significant transportation and communications network in the Earth-Moon spatial region.

Considering the significant number of payloads that will be required in this process, the mass-specific cost of launching these payloads, and the added risk and cost of human presence in space, it is clearly desirable to automate major parts of such an operation. One very costly and time-consuming factor in this picture is the delivery of payloads to the Moon. Foreseeable payloads would include atmospheric modules, inflatable habitat kits, energy and oxygen plant elements, ground vehicles, laboratory modules, crew supplies, etc. The duration of high-risk human presence on the Moon could be greatly reduced if all such payloads were delivered to the prospective base site in advance of crew arrival.

In this view, the idea of a "Self-Unloading Reusable Lunar Lander" (SURLL) arises naturally. The general scenario depicts the lander being brought to low lunar orbit (LLO) from Earth atop a generic Orbital Transfer Vehicle (OTV). From LLO, the lander shuttles payloads down to the lunar surface, where, by means of some resident, detachable unloading device, it deploys the payloads and returns to orbit. The general goal is for the system to perform with maximum payload capability, automation, and reliability, while also minimizing environmental hazards, servicing needs, and mission costs.

Our response to this demand is UM-Haul, or the UnManned Heavy Payload Unloader and Lander. The complete study includes a system description, along with a preliminary cost analysis and a design status assessment.

Design Development

The specific design requirements and constraints adopted are those formulated in the 1991 AIAA/Industry Design Competition Proposal Request for the SURLL. They are

1. Descent from LLO to the lunar surface carrying a 7000-kg payload, the unloading mechanism, and propellant for ascent back to LLO.
2. Capability to refuel and reload in LLO for another landing.
3. Capability to carry the unloading mechanism back to LLO for later use at another landing site.

4. Return to LLO without the unloading device, and bring down a payload of mass equal to 7000 kg plus that of the unloading device.

5. Capability to perform 10 landing/unloading sequences before major servicing.

6. Modularized subsystems for easy maintenance.

7. Ability to handle a payload of the same diameter as Space Station *Freedom* (SSF) logistics module.

8. The payloads need not be supplied with power or thermal control.

Earth systems are not acceptable SURLL solutions for a variety of reasons, most of which can be ascribed to the adverse conditions of the lunar environment: extreme temperatures, abrasive soils, low gravity, intense radiation, and the absence of atmosphere. Thus, whereas Earth cargo handling systems may provide useful functional concepts, the design of a lunar cargo delivery system is subject to some very different requirements. This tends to necessitate a "build from scratch" approach.

The design effort was subdivided into six technical subgroups: Payload/Spacecraft Integration, Structures, Propulsion, Power, Controls and Communications, and Mission Analysis. The subsystem designs are described below.

PAYLOAD AND SPACECRAFT INTEGRATION

Giving consideration to assembly, functionality, power, and thermal control needs, stability, and center of gravity locus, the Payload and Spacecraft Integration (PSCI) group integrated (i.e., placed and interconnected) the subsystem components within the spacecraft frames. External interfaces, including payload handling, were also addressed.

System Overview

UM-Haul consists of two main components: lander and unloader. The lander is a low center of gravity platform with four main engines, propellant tanks, a centralized cargo bay with deployable ramps, and four shock-absorbing retractable landing legs. The unloader is a solar-powered, telerobotic, eight-wheeled carrier vehicle that fits in the Lander's cargo bay. It utilizes a special lift mechanism in conjunction with legs mounted on the payload unit to deploy cargo on the lunar surface. The unloader can remain on the surface while the lander returns to orbit for another payload. A visual impression of the system is given in Fig. 1; Table 1 briefly summarizes features of the lander and unloader systems.

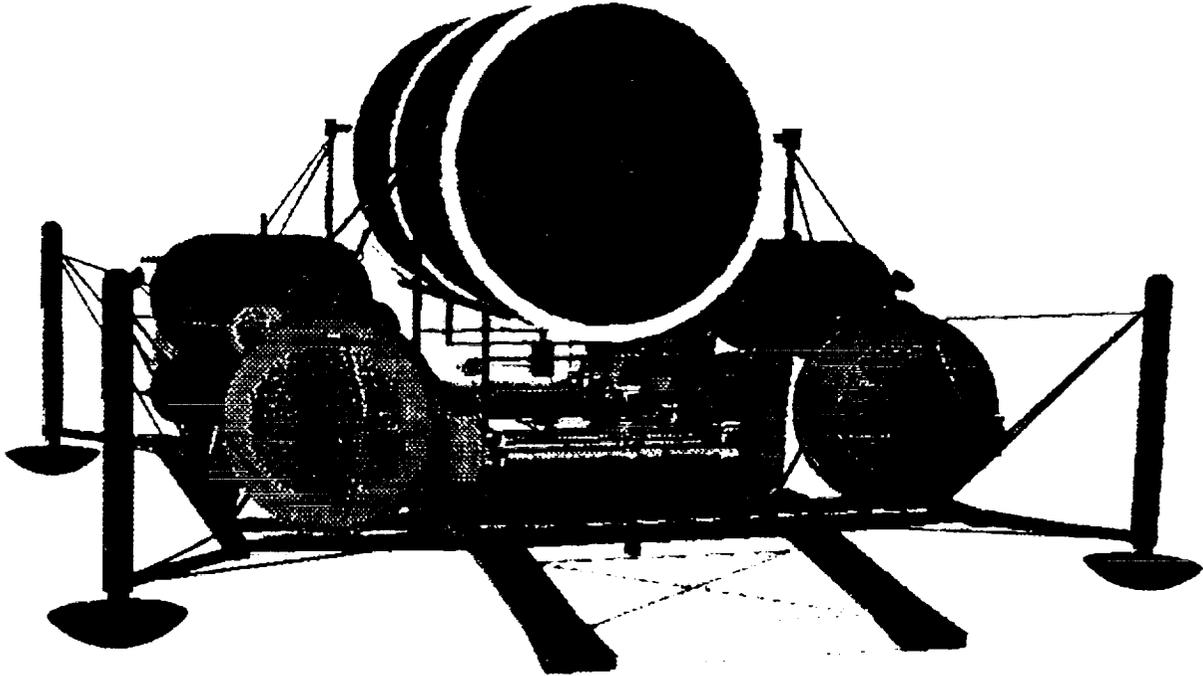


Fig. 1. The UM-Haul system.

TABLE 1. Summary of system features.

Function	Lander	Unloader
Propulsion		
Main Engine/Drive, Lift Motor	Pratt & Whitney RL10-IIIB (4)	DC Motors: 746 W (8,4)
RCS Thruster/Steering Motor	GH ₂ /OX8911 Bell Textron (20)	DC Motors: 373 W (8)
Power		
Primary Power System	GH ₂ GOX Fuel Cells (3)	GaAs/Ge Solar Array (4.5 m ²)
Secondary Power System		NaS Batteries (6)
Structure		
Structural Material	Al-Li 2090-T841	Al-Li 2090-T841
Structural Mass	3,409 kg	448 kg
Total Dry Mass	6,162 kg	1,438 kg
Payload Capacity	8,438 kg	8,438 kg
Landing Legs/Wheels	Pads, retractable (4)	Wire mesh, indep. drive, steer (8)
Suspension System	Helium Gas Shocks	Rotational Springs
Communications		
Frequency (Primary, backup)	Ka-Band, S-Band (Backup)	Ka-Band, S-Band (Backup)
Link to Unloader/Lander	Beacon (1)	Receiver (1)
Controls		
Obstacle Avoidance System	Laser Radar (1)	Television Cameras (4)
Guidance System Sensors		
Relative Frame:	Star Trackers (3)	Wheel Odometers (2)
Body Frame:	Ring Laser Gyroscopes (6)	Gyrocompasses (2)
Position, Velocity, Acc.:	Accelerometers (6)	Accelerometers (2)

OTV Interface

The lander refuels and receives new payloads regularly from a standard OTV. The OTV is fitted with a payload pallet/docking port for interface with the lander. The pallet arms hold the payload with four Light-Weight Longeron Latches (LWLLUs). A Payload Transfer Mechanism (PTM) sits in the middle of the pallet and guides the payload over to the lander when docked. Also on the pallet arms there are Docking/Fuel Ports (D/FP), which provide the fueling hookup with the lander.

Payload Interface

The general size and shape of the payload is an important characteristic of a transport system. For the sake of simplicity it was therefore decided to interpret Design Criterion #7 in a narrow sense, by adopting the SSF logistics module as the standard payload. The logistics module is cylindrical, 7.4 m long and 4.6 m in diameter; it has three bulkhead rings and a set of trunnion points for easy handling. For UM-Haul purposes, it became necessary to further furnish this payload with four deploying legs.

The lander receives a payload with four motorized trunnion latches mounted on special bearing truss members along the central unloader bay. These will completely secure the payload during transport. The holders are high enough to give clearance for the unloader in the bay underneath. After landing, the unloader uses special lifting posts to clear the payload from the lander truss.

While aboard the unloader, the payload rests on a set of rails with rocker joints. A trunnion, located at the base of the standard payload, fits into a cylindrical hardlock suspended from the unloader's lifting structure. This prevents the payload from shifting in the rails when the unloader is on a slope. At the time of deployment, the payload legs are released with the aid of pyrom pins, and lock into "standing" position. Using its lifting mechanism, the unloader slowly lowers the payload to the ground until it rests fully on the four legs.

System Launch and Assembly

The external dimensions of UM-Haul preclude integral launch with any existing or planned Earth Launch Vehicle (ELV). LEO assembly, at or near a permanently manned structure such as SSF, has therefore been envisioned. The space shuttle orbiter has the capacity to move the entire UM-Haul assembly kit to orbit in three launches, not including propellants. The modular design of the lander structure in particular helps contribute to the relative simplicity of in-orbit assembly.

STRUCTURES

The structural components of the UM-Haul system were designed to serve certain basic mission functions, and to provide support for the other subsystems. Emphasis was placed on strength and durability, while also seeking to minimize the total structural mass. A static analysis with beam theory was used throughout for loading strength calculations. Reliability and

redundancy are essential considerations due to the rigorous system lifetime requirements. The vital elements of the Lander and Unloader have been designed with a factor of safety that will allow for continued operation after unforeseen contingencies. The Unloader structure has a safety factor of 3, the Lander structure a safety factor of 1.5. For all major structural components, the material chosen is the alloy Al-Li 2090-T841, due to its low density and high yield strength.

Lander Structure

The Lander structure consists of the following main components: platform and unloader bay, engine shrouds, ramps, and landing legs. In the following, a brief description will be given of each component.

The platform is the "backbone" of the structure, with an area of 8×10 m, and designed to withstand 1g of landing deceleration with full loading. The unloader bay is located in the middle section of the platform and is characterized by a set of runners traversing the length of the platform. The ramps run off both sides of the unloader bay, and fold up to a vertical position during flight.

The engine shrouds provide the housing and restraint for the main engines. They are located near the middle of the platform on either side of the unloader bay. The maximum single-engine thrust of 33,000 N is used for the maximum loading calculations. The landing legs are retractable to give a low ground clearance (and thus low ramp slope) during unloader operations. They are designed with a helium gas shock system to absorb the impact of landing. Located diagonally outward from the platform corners, they attain a maximum distance from the engine plumes during landing and takeoff burns. The temperatures and dust blasts generated from the engines have a deteriorating effect on the landing legs.

Unloader Structure

The unloader structural system consists of a chassis, payload interface and handling system, suspension and steering systems, wheels, and subsystem support structures.

The chassis is the main support frame upon which all other unloader subsystems are attached. It is thus responsible for withstanding all stresses due to these subsystems and loads due to system operations. It consists of two longitudinal beams and four transversal spars assembled in a "block eight" configuration.

Inside the chassis frame there is a truss grid for support of various subsystem components such as radiators, instrument bays, solar arrays, batteries, etc. Of special importance is the solar array support, since the fragile semiconductor cells need protection from vibrations and dust kick-up. While the grid combines with the suspension for good vibration damping, the dust shielding is provided by a special "curtain."

Prominent on the unloader is the payload interface and handling system, which includes a set of threaded posts with housing rail posts, support rails, a set of rocker joints for the payload bulkheads, and a hardlock support. With the aid of four 746-W motors, this system performs the important task of securing and deploying (lifting/lowering) the payloads. Details of the system can be seen in Fig. 2.

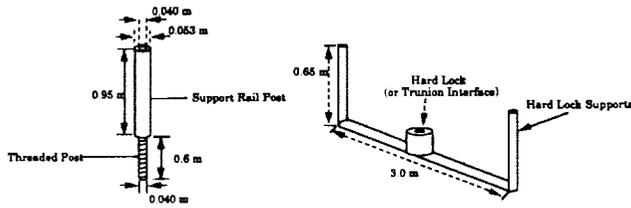


Fig. 2. Lifting posts and hard lock.

The unloader's eight wheels are of a wire mesh type, each independently driven and steered. The drive motors are 746 W each. The suspension consists of rotational springs. Details of the steering and suspension systems can be seen in Fig. 3.

PROPULSION

The focus of the propulsion design fell on selection of main engines and attitude thrusters (RCS). A design was conceived to integrate the primary propellant delivery system with the RCS and the fuel cell power system.

Engine Selection

After considering our mission's needs for thrust, throttability, durability, and cost-efficiency, the only viable candidates for main engines were the chemical liquid bipropellant (liquid oxygen and liquid hydrogen) rocket engines. Out of these, the cryogenic propellants took the edge over hypergolic propellants, having a high specific impulse (I_{sp}) and the prospect of symbiotic propellant usage with future OTV's.

With this category firmly in mind, a scan of presently and near-future available engines began. The chosen engine was Pratt & Whitney's RL10-IIIB, a derivative of the already existing Centaur RL10A-3-3A. Although the RL10-IIIB is still in a developmental stage, its predicted merits are very good: It has a maximum thrust of 33,360 N, an I_{sp} of 470 s, and a mass of only 180 kg.

The thruster chosen for the Reaction Control System is the Bell Aerospace 8911 GOX/GH2. The reverse flow chamber feature of this engine aids in the combustion process of the reactant gases, and thus achieves a good thrust without the need for a combustor.

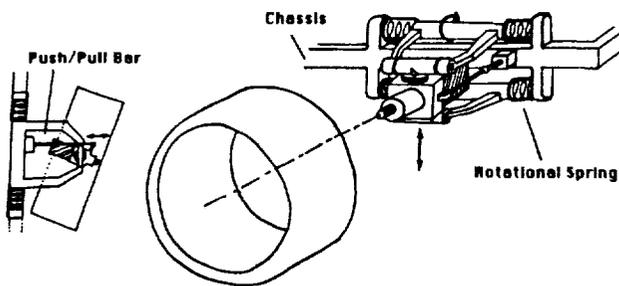


Fig. 3. Steering and suspension.

Propellant Storage and Delivery

The liquid oxygen (LOX) is stored in a set of big cylindrical tanks and the liquid hydrogen (LH_2) is stored in a set of big tanks, embedded in the trusswork in the neighborhood of the main engine shrouds on the lander. The reactants must be protected thermally since the boiling point of LOX is 90.4 K, and that of LH_2 a mere 20.2 K. Additionally, it is desirable to provide protection from debris and meteoroid strikes that might rupture the tank membrane.

For this purpose, a multilayer insulation has been chosen with 3.8 cm of Double Goldized Kapton reflectors separated by Dacron net for a total of 20 layers, covered by a Nomex resined face sheet and tension membrane.

The UM-Haul main engines employ a turbopump-fed delivery system with regenerative turbines; the LH_2 is used first to cool the engine nozzle; in passing through the nozzle jacket the LH_2 is vaporized and thus pressurized to drive the turbopump. Finally, the gaseous hydrogen arrives in the combustion chamber where it reacts with vaporized LOX and produces thrust.

It turns out that the RCS thrusters and the lander's power system fuel cells run on roughly the same chamber pressure. Since they also use the same reactants—gaseous hydrogen and oxygen—integrating them with the main propellant delivery system came naturally. The result is shown in Fig. 4. With the aid of miniturbopumps (labeled R1S), the liquid propellants are vaporized (2), in the process pressurizing small accumulator tanks (3) to operational level for the RCS thrusters and fuel cells. Note that the minipumps are regenerately driven by combustors (4) bleeding off reactants from the accumulator tanks.

POWER

The power systems of UM-Haul had to meet very strict demands. Selection of the proper system for endurance, efficiency, mass, and output level was imperative. Power architecture was developed throughout. A thermal management system was conceived, relieving subsystem-generated heat buildup.

Power Systems

The needs of the UM-Haul system are unusual. The unloader may be required to stay on the lunar surface for weeks with

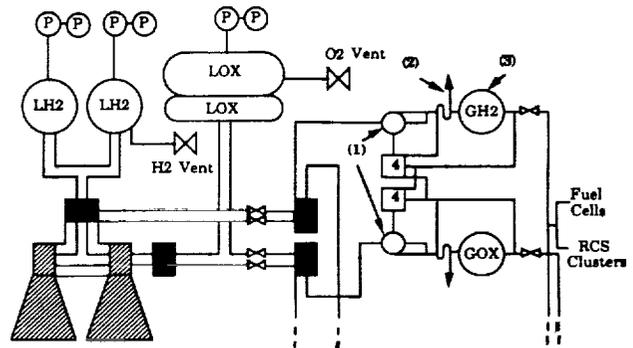


Fig. 4. Integrated propellant delivery system.

little or no activity, and suddenly called to duty with a big energy output. Although its cruise speed is only 0.1 km/hr, one must take into account that the unloader is carrying 5-6 times its own weight. The total energy estimate runs up to 7.2 kWhr for each unloader mission. Peak power is roughly 1200 W. For the lander, one sees a more modest, but steady consumption.

The primary and secondary power systems for the unloader are GaAs/Ge solar cells and NaS batteries, respectively. The lander power system consists of GH₂/GOX primary fuel cells, and since they feed off the generous supplies of the propulsion system, they can be used to charge the unloader batteries in special cases.

The GaAs/Ge solar array has 2800 cells, has an area of 4.5 m², and gives 600-800 W over 29 V. The energy is stored in the NaS batteries during periods of inactivity. The batteries have a normal operating temperature of 350°C, and lose efficiency with lower temperatures. Left to the cold lunar night at low discharge rate, they could freeze without a thermal management system. This will be discussed later.

The lander's fuel cells draw energy from the reaction of gaseous oxygen and hydrogen. They are located with the RCS reservoirs on the lander, near the main hydrogen tanks.

Thermal Management

The numerous power-driven units on the lander and on the unloader generate heat. This heat rapidly builds up unless it is led away; there is no atmosphere to conduct or convect heat, therefore one must radiate it through specially designed space radiators.

The thermal loads produced by the lander and unloader are 954 and 1480 W, respectively. Each heat generating unit will be connected with a heat pipe of aluminum (filled with mercury), thus transmitting excess heat through the pipe to the radiator. There is one radiator on each vehicle.

But not all systems want cooling; the NaS batteries on the unloader need heating, i.e., thermal insulation. The batteries will be put in a heat insulating box with a phase change substance, carbazole. This substance absorbs excess energy and releases it as it cools down and solidifies.

CONTROL AND COMMUNICATIONS

The design of Guidance, Navigation, and Control (GN&C) systems for UM-Haul involved selecting attitude and positioning sensors, obstacle avoidance systems, and processing hardware. Features of a communications system were developed.

Lander GN&C

The task of this system is to determine the position, velocity, and attitude of the spacecraft. Hazard avoidance (for landing) also plays an important role in this particular system. The four active components of the system are external referencing, inertial referencing, obstacle avoidance, and computer interaction/system integration.

The external (or "relative") referencing is achieved by a combining sensors (star trackers) with a vertically stabilized platform (the stars) to obtain an attitude reference. The inertial (or "body

frame") referencing is concerned with sensing changes in rotation and velocity. To this end it was decided to apply ring laser gyroscopes, one for each body axis. Ring laser gyroscopes are very sensitive, and accumulate less error than conventional momentum wheels and gyroscopes. The output from the laser gyroscopes is integrated by the onboard computer to give rotational changes. For the translational changes, an accelerometer is used.

An obstacle avoidance system is essential to safe landings by unmanned vehicles in the mostly unknown lunar terrain. A laser radar starts the scanning process approximately when the lander passes High Gate (880 m altitude) and continues to narrow its mesh as the lander approaches. Obstacle sites will be noted and avoided through careful interpretation by the onboard computer. The laser radar consumes 258 W of power.

The computer interaction and system integration is the process by which the onboard computers collect all the referencing data and digest it into position, attitude, velocity, and flight plan (commands from Earth). The Lander has three onboard computers, two of which are idle during most nonmaneuvering phases of the mission, but capable of taking over all functions of the other computer(s) should a malfunction occur.

Unloader GN&C

The unloader's GN&C system is composed of four ingredients: hazard sensing, path determination, motion sensing, and integration.

For hazard sensing, television cameras are employed, two at each end of the vehicle. This gives stereoscopic imaging opportunities, of great use in path determination. Disadvantages include ineffectiveness during lunar night and the delay in data transmission, given the nonautonomy of the system.

Path determination is an interactive process between the onboard computers and mission control (humans). The motion sensing is still provided by body-mounted accelerometers, but is supplied also by wheel odometers for positioning and gyrocompasses for heading.

The UM-Haul unloader employs the Computer-Aided Remote Driving (CARD) method of semiautonomous travel. The system integration diagram for a CARD method is shown in Fig. 5.

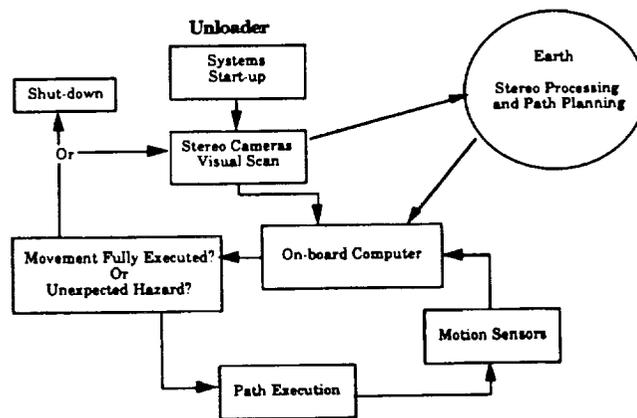


Fig. 5. Unloader CARD system.

To execute this system, the unloader employs two onboard computers, one of which is solely dedicated to the GN&C and CARD systems; the other is used for system resource management, troubleshooting, and back-up GN&C.

Communications System

The items to be communicated in the UM-Haul system are countless. Propulsion system monitoring, power system data, flight data, guidance aspects, and system diagnostics are but some general areas. It is clear that communications are essential to the success of any SURLL mission, and UM-Haul in particular.

The optimum link configuration involves the ground terminal (GT) path, i.e., direct transmission of data between the lunar surface and one of three continuously listening Earth stations (initial deployment). The Ka-band (20-40 GHz) was chosen as primary carrier frequency, with the S-band (2-4 GHz) as a backup frequency range.

The communications hardware includes 2 Ka-band and 2 S-band antennas for both lander and unloader. Likewise, on each vehicle there is a set of transmitters/receivers and a set of filter/switches for both Ka-band and S-band.

Communications and operation of UM-Haul would be greatly enhanced by the establishment of a lunar communications satellite.

MISSION ANALYSIS

Mission Analysis was chiefly responsible for obtaining a flight plan for the lander. A study was also done on mission timelines for selected landing sites, and on the line-of-sight conditions for various envisioned communications paths between the UM-Haul vehicles and other stations.

The Mission Cycle

For a better understanding of the UM-Haul operational concept, it is useful to subdivide the typical mission into five segments: initial in-orbit operations, transit to lunar surface, lunar surface operations, launch to orbit, and concluding in-orbit operations.

Initial in-orbit operations for a mission include payload transfer, systems check, descent planning, separation, and descent countdown. Transit to lunar surface consists of the descent orbit burn and a touchdown burn, possibly with hovering. The lunar surface operations involve another complete systems check, ramp deployment, unloader activation, cargo securing and transit, unloading, and finally a clearance or reboarding maneuver by the unloader.

Preceding the launch to orbit phase, yet another systems check is performed. A rapid ascent burn takes the lander up to LLO. An orbit insertion burn is required upon obtaining the desired altitude. Finally, during the concluding orbit operations, the lander waits in orbit for the arrival of another OTV. Rendezvous, proximity operations, and docking follow. Once safely docked, the lander is refueled and checked by the OTV. If 10 mission cycles have been completed, the entire system is returned to LLO for maintenance; otherwise, it is ready to load another payload and begin the next cycle.

Mission Planning

Mission analysis has been mainly concerned with the flight aspects of the mission cycle, insofar as they involve orbital mechanics and the preparation of a ΔV budget. ΔV s are velocity changes needed for a spacecraft to change its angular momentum and energy relative to a gravitating body and thus enter a new trajectory. It is the propulsion system(s) of the spacecraft that furnish these ΔV s, so for thrust and fuel consumption specifications the ΔV budget is of vital importance to the mission. Another budget of major significance is that of time.

Elements of the mission cycle with most direct bearing on the ΔV budget can be roughly categorized in three phases: rendezvous, descent, and ascent. The two main parameters in these scenarios are the lunar surface and the LLO parking orbit.

The parking orbit chosen for the lander is a circular LLO with an altitude of 111 km. This height was chosen with consideration orbital instabilities occurring below 93 km, and the increasing ΔV costs of higher orbits. The orbital period is 119', and the inclination angle (with respect to the lunar equator) is equal to the latitude of the next landing site.

The first (or last) event in the UM-Haul mission cycle is the rendezvous and docking between the lander and the OTV in LLO. It is clearly impractical to require a precise insertion of the incoming OTV in the close neighborhood of the waiting lander. (This would give narrow and infrequent launch windows in LEO.) Instead, the OTV is inserted into the 111-km orbit at some arbitrary phase angle away from the lander. The lander will now enter a 101-km chase orbit to catch up with the OTV. In the worst case, (i.e., when the initial phase angle is 360°) the lander will spend 10 days catching up. When the OTV is in sight and at a determined phase of 0.725° , the lander performs an ascent burn followed by a braking burn to rendezvous with the OTV (terminal phase maneuvers). After rendezvous, proximity operations must be executed in order to dock with the OTV.

For descent, the lander first separates from the OTV and then executes an engine burn for a retrograde ΔV of 21.8 m/s (descent orbit initiation), thus entering a Hohmann transfer ellipse to a perilune altitude of 15.24 km. At this point, the lander performs its powered descent initiation burn. The braking is considerable, as the total ΔV reaches 1693.8 m/s. A slow, increasingly vertical descent to the surface results. Limited hovering time is allowed for in the ΔV budget if the targeted landing spot turns out to be unfavorable.

After the surface operations are complete, the lander returns to LLO. This operation consists of three main parts: first, a rapid ascent burn ($\Delta V = 81.7$ m/s) to acquire altitude (thus avoiding risk of collisions); next, a forceful horizontal orbit insertion maneuver ($\Delta V = 1682.4$ m/s); finally, depending on the present orbital inclination, a dog-leg plane change maneuver will be required to poise the lander for its next mission.

Prospective Landing Sites

Four possible landing sites were selected for UM-Haul, mainly based on their suitability as prospective lunar outpost sites. Such candidacy is heavily determined by scientific interest and industrial promise. Due to the presently inadequate communi-

cations support, it is necessary to confine UM-Haul to nearside landings; In any case, topologically ideal sites were hard to find on the farside. However, the farside is of particular interest for radioastronomy observatories, since the Earth radio waves are blocked out. Two of our sites are therefore near the 90° parallels (E and W) where they actually librate out of Earth view for parts of every month. The sites are:

Lacus Veris (87.5°W, 13°S): Scientific Interest; access to farside.

Taurus-Littrow (30°E, 20°N): Mare region - O₂ production. Apollo 17 site.

Mare Nubium (20°W, 10°S): O₂ production. Near Apollo 12 site.

Mare Marginis (92.5°E, 9.5°N) O₂ production. Technically on farside.

CONCLUSION

A preliminary design has been developed for a Self-Unloading Reusable Lunar Lander, meeting the criteria stated in AIAA/Industry's Request for Proposal. The result, UM-Haul, comprises a lander/unloader system with capability to handle payloads up to 8438 kg. The hardware cost of one UM-Haul system is estimated at \$1.2 billion.

The following key areas need focus for the completion of the preliminary design: structural analysis (CAD, static, and dynamic), guidance system design, propellant delivery piping, engine power requirements, unloader AI implementation, telemetry design, system verification of margins, and cost analysis.

